Comparison of 6.5 kV Silicon and SiC Diodes

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***Abstract*—Silicon carbide (SiC) devices offer many advantages for the power electronics field. Even though there are commercial SiC diodes available, their use is limited to low power applications. This paper presents a SiC PIN diode module for medium voltage converters. The module, which has a rating of 6.5 kV and 1000 A, is compared to the commercial 6.5 kV, 1200 A Si diode DD600S65K1. The analysis is based on the static behavior (on-state and blocking characteristic) and exemplary waveforms for diode turn-on, diode turn-off and IGBT turn-on transients at 3000 V and 1000 A. Additionally, switching losses extracted out of measurements are plotted for currents between 50 and 1000 A at junction temperatures of 25 and 125°C.**

I. Introduction

Medium voltage converters (MVC) are essential for power generation and distribution systems, industrial drives and traction systems, among others. One of the limitations of silicon devices is their trade-off between conduction and switching losses. Therefore, for a given device structure and blocking capability, it is not possible to optimize a device for minimal conduction and switching losses simultaneously. [1]

Loss reduction is not the only aim in power semiconductor development. Features like higher power density capability (e.g. higher blocking voltages, high temperature operation), increased ruggedness and reliability are also sought. The maturity achieved by silicon devices makes a major breakthrough difficult. Hence, new wide band gap semiconductors, due to their superior physical properties, have become attractive for new developments in power electronics, including the field of MVC. [2]–[4]

SiC diodes have been commercially available for over a decade. Nevertheless, there is still no alternative for MVC. SiC material offer several advantages, such as a higher breakdown electric field, higher thermal conductivity and lower intrinsic carrier concentration. A higher breakdown electric field ($\approx$10 times that of Si) allows a higher doping in a thinner blocking layer, which reduces the on-state resistance. [2], [5]–[7]

A high thermal conductivity (3.7 vs. 1.5 W/cmK in Si) helps to remove the heat produced by the losses in the semiconductor. A lower intrinsic carrier concentration (several orders of magnitude smaller than Si) has a direct effect in the maximal operating temperature of the device. SiC devices can operate at high temperatures with leakage currents that are considerably smaller than those present in Si devices, as long as the package is designed accordingly [4], [6], [8]. As a consequence, bulky heat sinks used in converters could be reduced in size, or complex cooling systems could be simplified.

SiC diodes are also known for a minimal reverse recovery current peak, even at high switching speeds. This does not only reduce the losses in the SiC device itself, but it also diminishes the losses in the active switch during the turn-on transient.

There are three classes of SiC diodes being developed currently [3], [5]:

- Schottky barrier diodes, applied at blocking voltages under 3 kV due to leakage current problems.
- PIN diodes, which can block high voltages, but they have a relatively high on-state voltage.
- Junction Barrier Schottky (JBS) diodes, which merge characteristics of Schottky and PIN technologies.

The development of SiC diodes for high voltages (>3 kV) and high currents presents many challenges. Devices for high blocking voltages demand a complex packaging technology, in order to keep partial discharges, silicon gel stability and heat distribution under control. A balanced current distribution inside a module with a high number of paralleled chips demands an adeqcuate DCB layout that provides paths of equal stray inductance. [7], [9]

This paper presents a SiC PIN diode module for MVC, with a current rating of 1000 A and a blocking voltage of 6.5 kV and compares it to an equivalent Si diode available in the market. The chip design as well as the module design and their challenges are discussed and its static and switching properties are investigated. Complementary work can be found in [10]–[14].

II. Diode chip and module

SiC diode module prototypes capable of handling voltages over 4 kV and currents of at least 400 A were presented in [15], [16]. Both have a different approach on module design. In [15], a 4.5 kV, 1000 A diode capable of withstanding up to 300°C is introduced. The module has 5 SiC PiN diode chips of 64 mm^2 connected in parallel inside a resin mold package. Another approach to module design is made in [16]: An hybrid module IEGT/SiC PiN diode rated for 4.5 kV and 400 A is used in a 2.75 kV, 1 MVA inverter. The module is made of four 100A submodules connected in parallel. In total, 20 diode chips and 10 IEGT chips are used. The active area

This work was financially supported by the German Federal Ministry of Education and Research (BMBF).

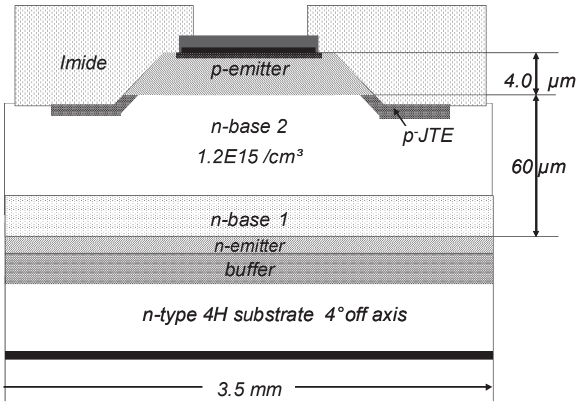


Figure 1. SiC diode chip design cross section [11]

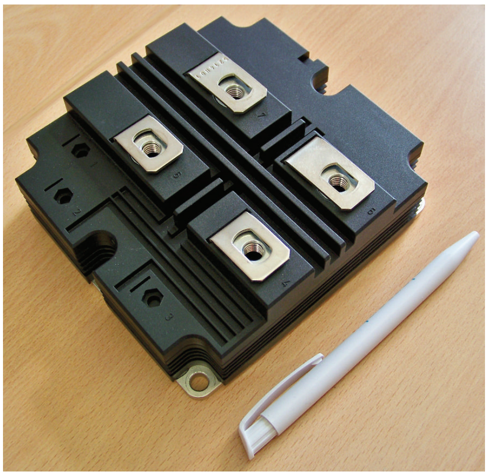


Figure 2. 6.5 kV, 1 kA SiC diode module

of each diode is 16 mm^2, details about diode design can be found in [17].

For the diode chips used in the module presented here, the basic structure is shown in Fig. 1. Each die has a size of 3.5 mm×3.5 mm with an anode area of 7.1 mm^2. Detailed information about chip design and fabrication can be found in [11]. A comparison of the SiC chips mentioned above is summarized in Tab. I. The table lists the active area of each SiC chip, the current density at nominal current rating, the on-state voltage and the nominal blocking voltage. The higher current density observed in [15] is a direct consequence of the reduced voltage blocking capabilities (4.5 kV). Diodes presented [17] and [11] show similar parameters, although [17] has the advantage of a bigger die size (2.2 times larger).

The module design uses the same dimensions from already commercially available Si diode module packaging for 6.5 kV with dimensions of 130×140×48 mm. The nominal values of the diode module are comparable to those of the Si diode DD600S65K1 used in the comparison: 6.5 kV, 2×500 A (SiC) vs. 6.5 kV, 2×600 A (Si). Both SiC and Si diode modules consist of two diode systems than can be used independently

Table I
SiC DIODE CHIPS COMPARISON

Publication, year	Active area (mm^2)	Current density (A/cm^2)	On-state voltage^a(V) @100 A/cm^2	Voltage rating (kV)
[15], 2008	64^b	313	3.6	4.5
[17], 2010	16	125	3.38	6
[11], 2010	7.1	176	3.42	6.5

[a] Room temperature, best result presented in paper.
[b] Not mentioned if the area represents total or active area.

or connected in parallel, which means that the SiC module can handle currents of 1 kA, when both diodes are connected in parallel. Inside the SiC diode module there are 4 DCB, each with 20 SiC diode chips. For 80 SiC chips per module, an active area of 5.68 cm^2 is achieved [11], [12]. The diode module DD600S65K1 contains 24 Si chips with an active area of 84.6 mm^2 each, totalizing an active area of 20.3 cm^2 per module. For the results shown in the paper, full Si and SiC modules where used (both anode-cathode pairs connected in parallel).

One of the critical issues in SiC diode chip design is the problem of forward degradation, which needs to be solved in order to get a better yield and lower the costs. It originates in existing substrate crystal defects in SiC, which have a direct effect in the degradation of the forward characteristic, reducing the active area of the chip and, thus, increasing the on-state voltage [6]. Cost is not a minor issue in SiC semiconductor manufacturing, which will stay high as long as no appropriate technique enables a production of large defect-free wafers [18].

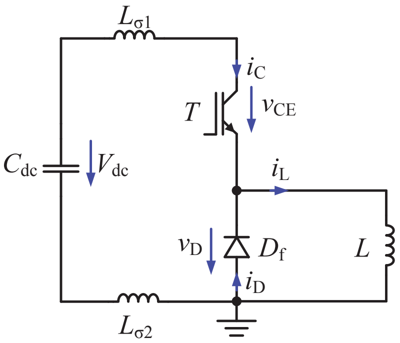
In module design, ways of reducing peaks in the electrical field distribution are sought, including adequate passivation methods and optimal direct copper bonded substrate technology [19]. New materials than can be applied in an extended high temperature range (>125°C) are also part of current investigations [13].

III. TEST BENCH SETUP

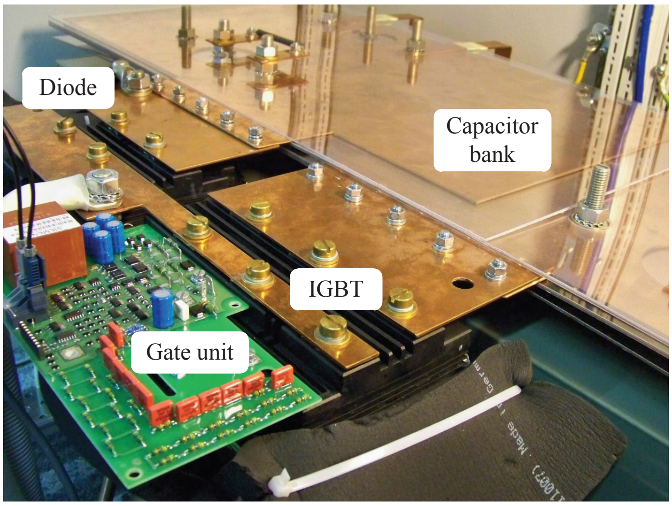
The test circuit is a buck converter, which allows the study of the switching behavior of an active switch T and its corresponding freewheeling diode D_f through the use of a double-pulse switching pattern, see Fig. 3a.

A robust mechanical design was accomplished using 2 mm-thick planar bus bars connecting the dc link capacitor C_dc (composed of two 1 mF capacitors in parallel) and the modules, see Fig. 3b. The load L is an air core inductor of 1 mH. The stray inductance of the commutation circuit (C_dc, L_σ, T, D_f) has a value of 235±10 nH. For simplicity, this inductance is represented by two concentrated inductors $L_{\sigma 1}$, $L_{\sigma 2}$ in Fig. 3a.

The junction temperature of the devices is controlled by a heating/cooling device, which sets the temperature of the liquid that flows through the plate where the modules are attached to. The dc link capacitor is charged by a high-voltage



(a)



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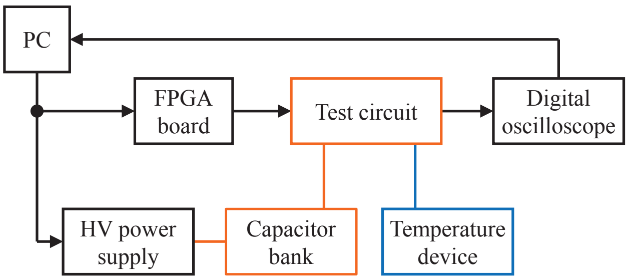


(c)

Figure 3. Test bench (a) schematic diagram of test circuit (T FZ600R65KF2, C_{dc} = 2 mF, $L_{\sigma1+2}$ = 235 nH, L = 1 mH) (b) experimental setup photo, (c) block diagram

power supply before the measurements are carried out. A partially automated measurement system was used. The values of V_{dc} and I_L are set using a LabVIEW program on a PC connected to the test bench. The measurements are captured by an 8 bit four-channel 200 MHz digital oscilloscope (LeCroy 24MXs-B), capable of working at a sample rate of 2.5 GS/s. A block diagram of this setup can be found in Fig. 3c.

The switch T used in the test is a 6.5 kV IGBT from Infineon, model FZ600R65KF2, with a nominal current rating of 600 A. It is operated with an industrial gate unit that has an output power of 3.5 W and a gate voltage of –10 V (off) and +15 V (on).

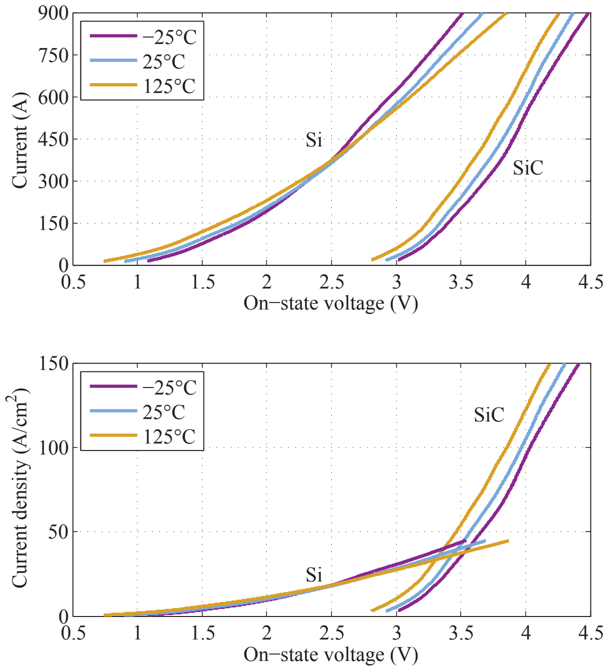


Figure 4. Diode on-state voltage at -25, 25 and 125°Cin terms of total current (up) and current density (down). Si: diode DD600S65K1 (full module), SiC: SiC diode, 80 chips in parallel.

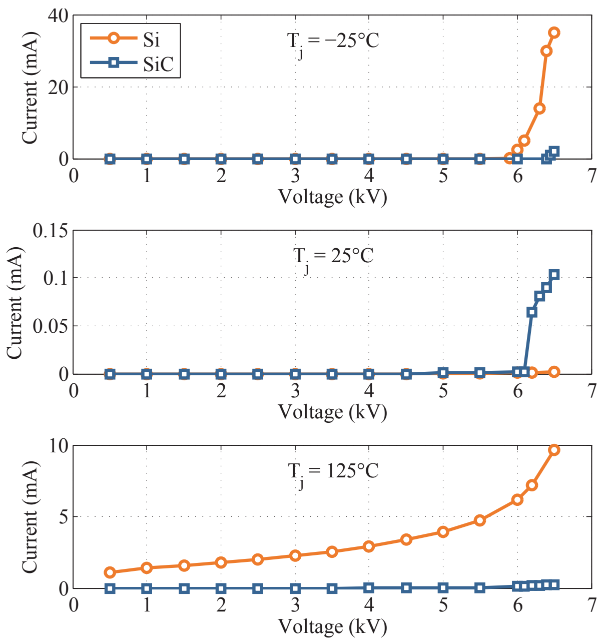


Figure 5. Reverse blocking characteristic at -25, 25 and 125°C. Si: diode DD600S65K1 (full module), SiC: SiC diode, 80 chips in parallel.

IV. SiC DIODE MODULE PROPERTIES

A. Static behavior

Fig. 4 shows the measured forward characteristic for the Si and SiC diodes at temperatures of –25°C , 25°C and 125°C. The forward voltage at 500 A and 25°C is 2.83 V for the Si diode and 3.89 V for the SiC diode. Furthermore, at 125°C it is 2.85 V for the Si diode and 3.75 V for the SiC diode. The Si diode shows a positive temperature coefficient for currents above 350 A. This is favorable for the thermal stability of parallel connected chips. On the other side, SiC diode exhibits a negative temperature coefficient of approximately −1.4 mV/K, which is in accordance to previous measurements done to single diode chips [11].

Considering the current density, the advantages of the SiC as material become clear. For a similar on-state voltage the SiC diode can handle an about two times larger current density. Instead of the typical current densities of 50 to 75 A/cm^2 at which Si diodes are usually operated, 6.5 kV SiC diodes achieve densities that are at least two times higher.

The reverse blocking characteristic at –25°C , 25°C and 125°C can be seen in Fig. 5. As expected, the leakage current of the Si diode presents a strong dependency on the junction temperature. The leakage current is kept under 1 µA for voltages below 6.5 kV at 25°C and below 5.9 kV at –25°C. It rises up to about 9.6 mA for 6.5 kV at 125°C. Moreover, the –25°C junction temperature reduces the breakdown voltage of the Si diode to about 6 kV. The SiC diode presents a weak dependency of the junction temperature, the breakdown voltage changes between 6.4 and 6.5 kV for temperatures between –25°C and 125°C and the leakage current is kept under 2 µA for voltages under 6 kV for all temperatures.

B. Switching behavior

The switching behavior of the SiC diode with a 6.5 kV IGBT FZ600R65KF2 was investigated. The diode turn-on, diode turn-off and the IGBT turn-on transients are of interest for the SiC diode operation. As a reference, Si diode DD600S65K1 was also measured. Both pairs (IGBT + SiC diode and IGBT + Si diode) were tested under identical conditions, including e.g. IGBT gate drive, dc link voltages, junction temperature and stray inductance.

Fig. 6 shows an example of the commutation transient waveforms at 3 kV and 1 kA for T_j = 25°C and T_j = 125°C, with a di/dt of approximately 1.5 kA/µs. Figs. 6a and 6b focus on the diode turn-on transient. The SiC diode is not influenced by the variation of the junction temperature, whereas the Si diode presents a considerably high forward recovery peak of 315 V and a slightly lower di/dt for T_j = 125°C. This leads to turn-on losses of about 0.4 J, compared to the relatively constant losses in the SiC diode under 0.1 J.

Figs. 6c and 6d present the diode turn-off transient. The SiC diode has a small reverse recovery current, which drastically reduce the losses. As a drawback, some ringing is present in the device current waveforms, which can also be seen in the device voltage waveforms. This problem has been addressed in some papers, e.g. [9], [10]. Basically, it is a consequence of the parallel connection of the chips inside the module and the snappy behavior of the diode due to its low tail charge. [20], [21] Possible solutions at chip design level are being investigated. Moreover, an optimized layout of the module and power circuit should also bring some improvement.

The SiC diode presents a softer behavior with reduced ringing and larger losses at T_j = 125°C (10 mJ at T_j = 25°C and 72 mJ at T_j = 125°C). The Si diode presents a higher reverse recovery current maximum and losses (0.75 J at T_j = 25°C and 1.75 J at T_j = 125°C). It is noteworthy that the turn-on losses of SiC diodes are comparable to the turn-off losses and their contribution to the overall diode losses is marginal. The turn-on losses at 125°C are about 81 mJ and the turn-off losses at 125°C are about 72 mJ.

Figs. 6e and 6f present the IGBT turn-on transient. The reduction of the reverse recovery current peak reduces also the stress and losses of the IGBT during the turn-on transient. The peak current was reduced from 1.69 kA to 1.19 kA and the IGBT turn-on losses at 125°C from 11.2 J to 5.7 J, when switched together with a SiC diode.

The commutation losses for both diode and IGBT were extracted from the measurements, the results can be seen in Fig. 7. The advantages of SiC technology regarding switching losses can be clearly seen. The transient behavior and losses of the SiC diode are almost independent from the junction temperature, see Figs. 6 and 7.

The turn-on losses for the SiC diode at 1000 A and 125°C (80 mJ) are about five times smaller than those of the Si-diode (440 mJ), but in the same order of magnitude of the SiC turn-off losses. The turn-off losses for the SiC diode at 1000 A and 125°C (72 mJ) are about twenty five times smaller than those of the Si-diode (1740 mJ). Correspondingly, the IGBT turn-on losses at 1000 A and 125°C with SiC diode are also reduced in about 50%.

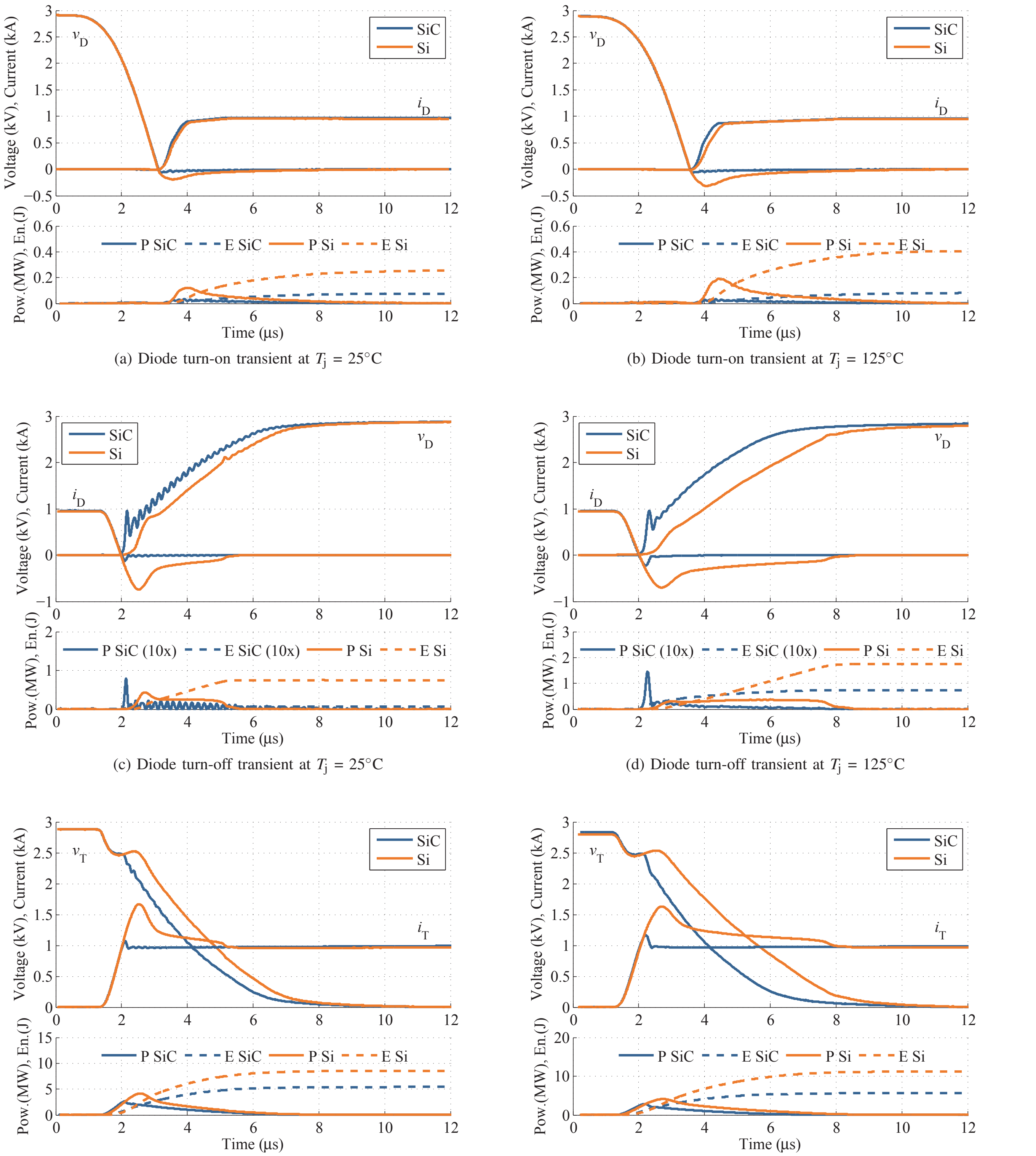
Lower losses could be obtained by reducing the IGBT's gate unit turn-on gate resistance, i.e. increasing the current change rate di/dt. Si diodes are limited by the reverse recovery current peak, which increases for higher di/dt values. In SiC diodes that limitation does not exist, although ringing and overvoltages due to the commutation stray inductance stray inductance L_σ need to be kept under control.

As a summary of the discussed parameters Table II offers a comparison of Si and SiC diode technologies operating at 3 kV and 600 A, regarding on-state voltage, leakage current and switching losses.

V. CONCLUSIONS

This paper has presented a functional diode module prototype rated for 6.5 kV and 1000 A and compared its performance to a commercial Si diode. The main challenges involved in chip and module design have been outlined.

The current prototype is able to switch the desired current (1000 A per module) successfully. The forward characteristics shows acceptable levels of on-state voltage, though higher than the Si counterpart. The reverse blocking properties of SiC,



(a) Diode turn-on transient at T_j = 25°C

(b) Diode turn-on transient at T_j = 125°C

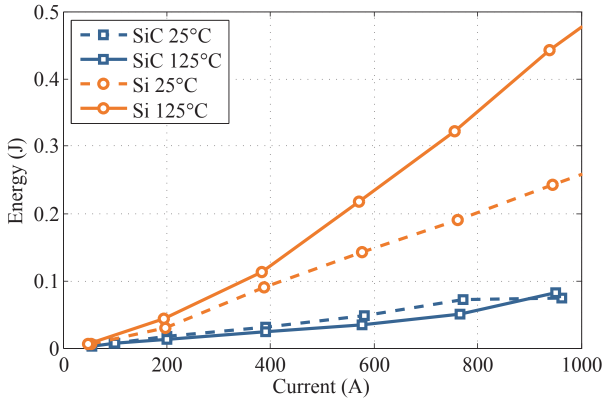
(c) Diode turn-off transient at T_j = 25°C

(d) Diode turn-off transient at T_j = 125°C

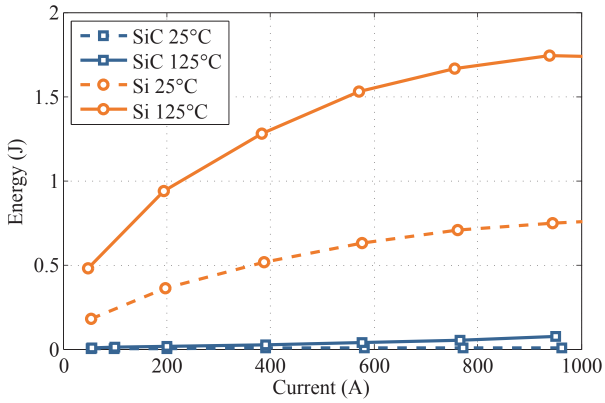
(e) IGBT turn-on transient at T_j = 25°C

(f) IGBT turn-on transient at T_j = 125°C

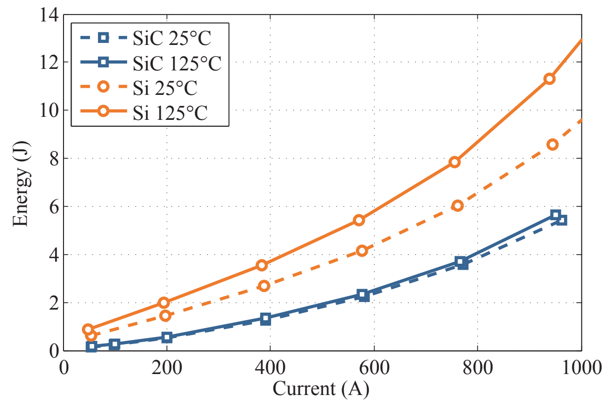
Figure 6. Commutation waveforms at V_{dc} = 3 kV, I_D = 1 kA, di/dt = 1.8 kA/μs at T_j = 25°C and 1.6 kA/μs at 125°C, IGBT FZ600R65KF2 and Si diode DD600S65K1



(a) Diode turn-on losses



(b) Diode turn-off losses



(c) IGBT turn-on losses

Figure 7. Switching losses at V_{dc} = 3 kV and I_D = 50…1000 A, di/dt = 1.6 kA/μs at T_j = 25°C and 1.8 kA/μs at 125°C for I_D = 1 kA, IGBT FZ600R65KF2 and Si diode module DD600S65K1 (full)

on the other hand, exhibit a very low leakage current and a satisfactory blocking capability. The SiC diode properties do not have a strong temperature dependency, as observed in Si diodes.

The switching behavior has still some issues regarding ringing, but offers marginal losses with low device stress. Further reduction can be achieved by increasing the di/dt

Table II
MAIN DATA OF SI AND SIC DIODES AT 3 KV AND 600 A

Diode	Silicon		Silicon carbide	
Temperature	25°C	125°C	25°C	125°C
On-state voltage	3.06 V	3.11 V	4.01 V	3.89 V
Leakage current	<1 μA	2.26 mA	<1 μA	<1μ A
$E_{on,diode}$	0.15 J	0.23 J	51 mJ	36 mJ
$E_{off,diode}$	0.64 J	1.55 J	7 mJ	41 mJ
$E_{on,IGBT}$	4.39 J	5.80 J	2.39 J	2.51 J
$E_{off,IGBT}$	2.30 J	2.78 J	2.25 J	2.64 J
$\sum E$	7.48 J	10.36 J	4.70 J	5.23 J

through the IGBT gate resistor, as the reverse recovery peak is not limiting factor in SiC diodes. The reduction of losses in the IGBT by the inclusion of a SiC freewheeling diode was also demonstrated, which amount to 50% for the turn-on transient at 125°C.

The reduction of semiconductor losses through the use of SiC devices will allow a higher power output for converters without increasing their size, or a reduction of the filter size in case a switching frequency increase is preferred. SiC technology development is currently in a breakthrough phase, meaning that the coming years will open new applications fields. Medium voltage converters will be a part of that new scenario.

REFERENCES

[1] W.-T. Franke and F. Fuchs, "Comparison of switching and conducting performance of SiC-JFET and SiC-BJT with a state of the art IGBT," in *Power Electronics and Applications, 2009. EPE '09. 13th European Conference on*, Sept. 2009.

[2] T. Kimoto, "SiC technologies for future energy electronics," in *VLSI Technology (VLSIT), 2010 Symposium on*, June 2010, pp. 9–14.

[3] M. Ostling, R. Ghandi, and C. Zetterling, "SiC power devices: present status, applications and future perspective," in *Power Semiconductor Devices and ICs (ISPSD), 2011 IEEE 23rd International Symposium on*, May 2011, pp. 10–15.

[4] N. Kaminski, "State of the art and the future of wide band-gap devices," in *Power Electronics and Applications, 2009. EPE '09. 13th European Conference on*, Sept. 2009.

[5] J. Hefner, A.R., R. Singh, J.-S. Lai, D. Berning, S. Bouche, and C. Chapuy, "SiC power diodes provide breakthrough performance for a wide range of applications," *Power Electronics, IEEE Transactions on*, vol. 16, no. 2, pp. 273–280, Mar. 2001.

[6] R. Singh, "Reliability and performance limitations in SiC power devices," *Microelectronics Reliability*, vol. 46, no. 56, pp. 713 – 730, 2006.

[7] P. Friedrichs, "SiC power devices for industrial applications," in *Power Electronics Conference (IPEC), 2010 International*, June 2010, pp. 3241–3248.

[8] P. Neudeck, R. Okojie, and L.-Y. Chen, "High-temperature electronics - a role for wide bandgap semiconductors?" *Proceedings of the IEEE*, vol. 90, no. 6, pp. 1065 – 1076, jun 2002.

[9] G. Miller, "New semiconductor technologies challenge package and system setups," in *Integrated Power Electronics Systems (CIPS), 2010 6th International Conference on*, March 2010.

[10] W. Bartsch, R. Elpelt, R. Schoerner, K.-O. Dohnke, B. Bloecher, and K. Koerber, "Bipolar 6.5 kV-SiC-diodes: on the road to industrial application," in *Power Electronics and Applications, 2005. EPE '05. 13th European Conference on*, Sept. 2005.

[11] D. Peters, W. Bartsch, B. Thomas, and R. Sommer, "6.5 kV SiC PiN diodes with improved forward characteristics," in *Materials Science Forum*, vol. 645. Trans Tech Publ, 2010, pp. 901–904.

[12] D. Peters, B. Thomas, T. Duetemeyer, T. Hunger, and R. Sommer, "An experimental study of high voltage SiC PiN diode modules designed for 6.5kV / 1kA," in *Materials Science Forum*, vol. 679. Trans Tech Publ, 2011, pp. 531–534.

[13] K. Dohnke, W. Bartsch, R. Schörner, and T. Van Weelden, "A molded package optimized for high voltage SiC-devices," in *Materials Science Forum*, vol. 679. Trans Tech Publ, 2011, pp. 762–765.

[14] K. Dohnke, D. Peters, and R. Schörner, "Characterization of packaged 6.5 kv sic pin-diodes up to 300 c," in *Materials Science Forum*, vol. 717. Trans Tech Publ, 2012, pp. 957–960.

[15] Y. Sugawara, S. Ogata, S. Okada, T. Izumi, Y. Miyanagi, K. Asano, K. Nakayama, and A. Tanaka, "4.5 kV 1000 A class SiC pn diode modules with resin mold package and ceramic flat package," in *Power Semiconductor Devices and ICs (ISPSD), 2008 IEEE 20th International Symposium on*, May 2008, pp. 267–270.

[16] K. Takao, Y. Tanaka, K. Sung, K. Wada, T. Shinohe, T. Kanai, and H. Ohashi, "High-power converters with high switching frequency operation using SiC-PiN diodes and Si-IEGTs," in *Electric Power Equipment - Switching Technology (ICEPE-ST), 2011 1st International Conference on*, Oct. 2011, pp. 412–417.

[17] Y. Tanaka, H. Ohashi, K. Sung, K. Takao, K. Wada, and T. Kanai, "Development of 6kV-class SiC-PiN diodes for high-voltage power inverter," in *Power Semiconductor Devices and ICs (ISPSD), 2010 IEEE 22nd International Symposium on*, June 2010, pp. 213–216.

[18] N. Kondrath and M. Kazimierczuk, "Characteristics and applications of silicon carbide power devices in power electronics," *International Journal of Electronics and Telecommunications*, vol. 56, no. 3, pp. 231–236, 2010.

[19] J.-H. Fabian, S. Hartmann, and A. Hamidi, "Analysis of insulation failure modes in high power igbt modules," in *Industry Applications Conference, 2005. Fourtieth IAS Annual Meeting. Conference Record of the 2005*, vol. 2, oct. 2005, pp. 799 – 805 Vol. 2.

[20] R. Hermann, S. Bernet, Y. Suh, and P. Steimer, "Parallel connection of Integrated Gate Commutated Thyristors (IGCTs) and diodes," *Power Electronics, IEEE Transactions on*, vol. 24, no. 9, pp. 2159–2170, Sept. 2009.

[21] J. Lutz, H. Schlangenotto, U. Scheuermann, and R. De Doncker, "Power device-induced oscillations and electromagnetic disturbances," in *Semiconductor Power Devices*. Springer Berlin Heidelberg, 2011, pp. 475–495.